

# NA49/NA61: results and plans on beam energy and system size scan at the CERN SPS<sup>1</sup>

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## Abstract

This paper presents results and plans of the NA49 and NA61/SHINE experiments at the CERN Super Proton Synchrotron concerning the study of relativistic nucleus-nucleus interactions. First, the NA49 evidence for the energy threshold of creating quark-gluon plasma, the onset of deconfinement, in central lead-lead collisions around 30.4 GeV is reviewed. Then the status of the NA61/SHINE systematic study of properties of the onset of deconfinement is presented. Second, the search for the critical point of strongly interacting matter undertaken by both experiments is discussed. NA49 measured large fluctuations at the top SPS energy, 158.4 GeV, in collisions of light and medium size nuclei. They seem to indicate that the critical point exists and is located close to baryonic chemical potential of about 250 MeV. The NA61/SHINE beam energy and system size scan started in 2009 will provide evidence for the existence of the critical point or refute the interpretation of the NA49 fluctuation data in terms of the critical point.

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# The NA61/SHINE Collaboration

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## 1 Introduction

In 1999 the NA49 experiment at the CERN Super Proton Synchrotron started a search for the onset of quark-gluon plasma (QGP) [1] creation with data taking for central Pb+Pb collisions at 40A GeV. Runs at 80A and 20A, 30A GeV followed in 2000 and 2002, respectively. This search was motivated by predictions of a statistical model of the early stage of nucleus–nucleus collisions [2] that the onset of deconfinement should lead to rapid changes of the energy dependence numerous hadron production properties, all appearing in a common energy domain. The conjectured features were observed [3, 4] around 30A GeV and dedicated experiments, NA61/SHINE at the CERN SPS and the Beam Energy Scan at BNL RHIC, continue detailed studies in the energy region of the onset of deconfinement.

Hadrons produced in collisions of light and medium size nuclei at collision energies higher than the energy of the onset of deconfinement may freeze-out just below the transition line between hadron gas and QGP. Thus their production properties may be sensitive to properties of the transition. In particular, freeze-out in the vicinity of the critical point may lead to a characteristic pattern of event-by-event fluctuations [5]. Motivated by these predictions NA49 and NA61/SHINE at the CERN SPS as well as STAR and PHENIX at the BNL RHIC have started a systematic search for the critical point.

The two sketches presented in Fig. 1 illustrate the basic ideas behind the experimental strategies in the search for and the study of the onset of deconfinement and the critical point.

In this report results of NA49 and plans of NA61/SHINE concerning the onset of deconfinement (Section 2) and the critical point (Section 3) are briefly presented.

## 2 Onset of Deconfinement

The detailed review of the experimental and theoretical status of the NA49 evidence for the onset of deconfinement can be found in the recent review [4]. The evidence is based on the observation that numerous hadron production properties measured in central Pb+Pb collisions change their energy dependence in a common energy domain (starting from about 30A GeV) and that these changes are consistent with the predictions for the onset of deconfinement. The four representative plots with the structures referred to as *horn*, *kink*, *step* and *dale* [4] are shown in Fig. 2.

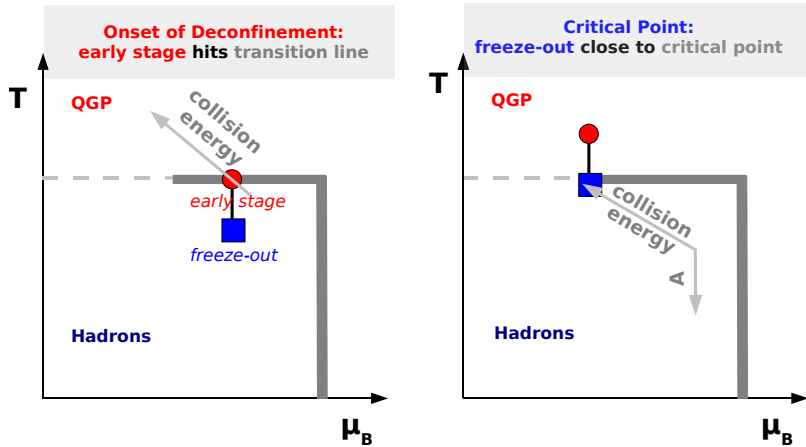


Figure 1: Sketches illustrating the basic ideas behind the experimental search for and the study of the onset of deconfinement (*left*) and the critical point (*right*). The transition line between hadron gas and quark-gluon plasma is indicated by solid (1<sup>st</sup> order transition) and dotted (cross-over) lines, which meet at the critical point (2<sup>nd</sup> order transition). The parameters of matter created in A+A collisions at the early stage and at freeze-out are indicated by the closed circle and square, respectively. Their dependence on collision energy and size of colliding nuclei is shown by arrows.

At Quark Matter 2011 new data from the RHIC beam energy scan with gold nuclei [6] and the Large Hadron Collider 2010 run with lead nuclei at 2.76 TeV [7] were presented. They strongly support the NA49 evidence for the onset of deconfinement. The RHIC results [6] confirm the NA49 measurements at the onset energies. The LHC data demonstrate that the energy dependence of hadron production properties shows rapid changes only at the low SPS energies. A smooth evolution is observed between the top SPS (17.2 GeV) and the current LHC (2.76 TeV) energies. This agrees with the interpretation of the NA49 structures as due to the onset of deconfinement and the expectation of only a smooth evolution of the quark-gluon plasma properties with increasing collision energy above the onset energy. As an example the energy dependence of the  $K^+/\pi^+$  ratio at mid-rapidity for central Pb+Pb (Au+Au) collisions with the new RHIC and LHC data is shown in Fig. 3 *left*. The STAR and ALICE measurements of identified particle spectra are restricted to the mid-rapidity region and transverse momenta larger than several hundred MeV/c. This is illustrated in Fig. 3 *right*, where a schematic comparison of the NA49 and STAR acceptances at 30A GeV is shown. Thus it is important to note that the collider results presented in Fig. 3 *left* include extrapolation to  $p_T = 0$  which increases systematic uncertainty of the results.

The observed signals of the onset of deconfinement concern single particle pro-

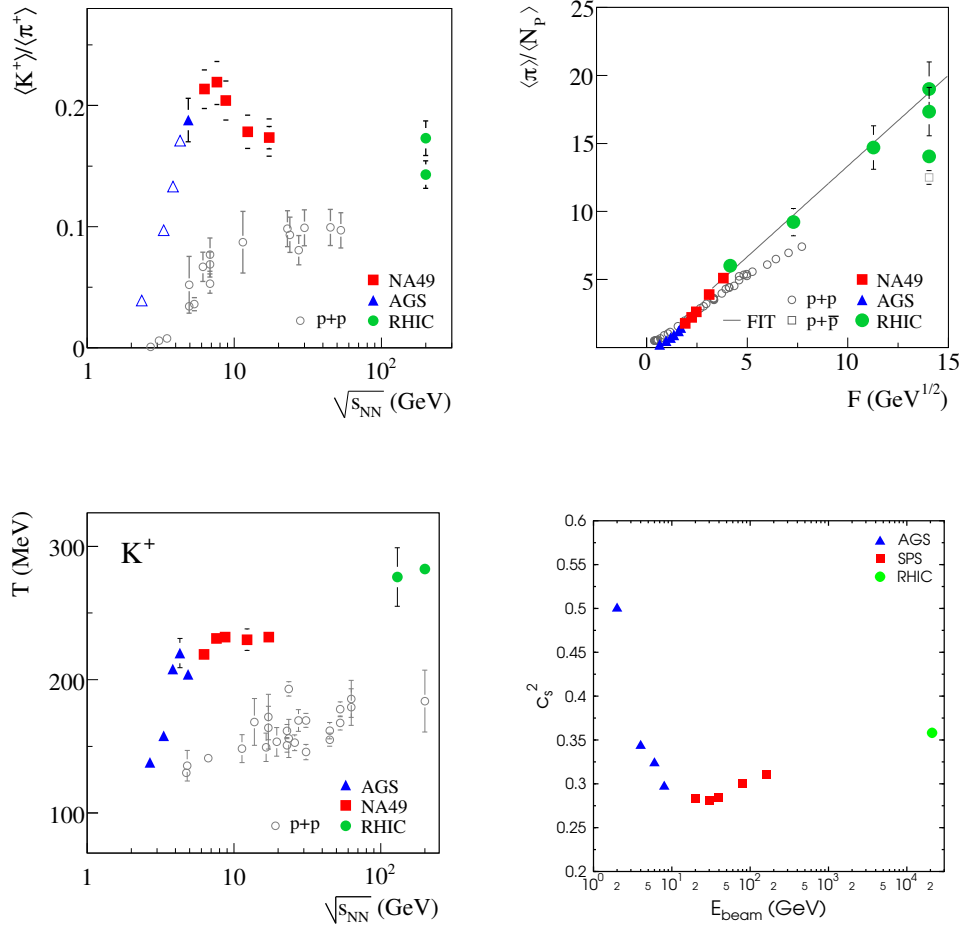


Figure 2: Heating curves of strongly interacting matter. Hadron production properties (see Ref. [4] for details) are plotted as a function of collision energy for central Pb+Pb (Au+Au) collisions and p+p interactions (open circles). The observed changes of the energy dependence for central Pb+Pb (Au+Au) collisions are related to: decrease of the mass of strangeness carries and the ratio of strange to non-strange *dof* (*horn*: top-left plot), increase of entropy production (*kink*: top-right plot), weakening of transverse (*step*: bottom-left plot) and longitudinal (*dale*: bottom-right plot) expansion at the onset of deconfinement.

duction properties. The search for signals in particle correlations and event-by-event fluctuations is up to now inconclusive [4]. Moreover, the energy dependence of event-by-event  $K/\pi$  and  $K/p$  fluctuations measured by NA49 and STAR in central Pb+Pb (Au+Au) collisions, is different [8, 9]. Both collaborations work on clarification of the observed differences.

An important part of the ion program of the NA61/SHINE experiment at the CERN SPS is the study of the properties of the onset of deconfinement [10]. NA61

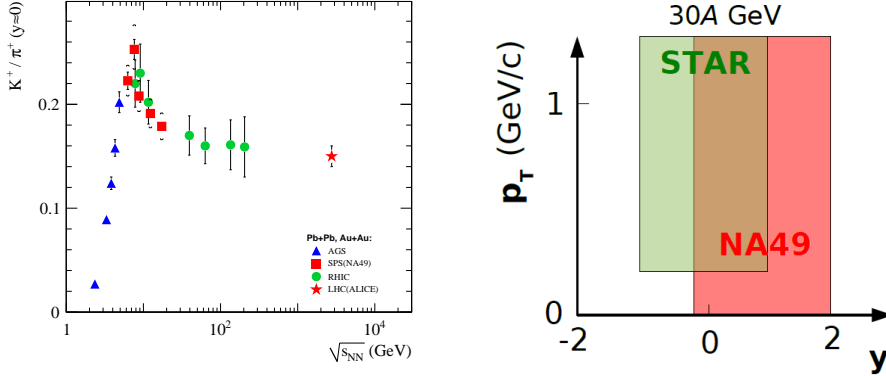


Figure 3: *Left* : Energy dependence of the  $K^+/\pi^+$  ratio at mid-rapidity for central Pb+Pb (Au+Au) collisions showing also the new RHIC and LHC data. *Right* : Schematic comparison of the NA49 and STAR acceptance for measurements of identified hadrons at 30A GeV in transverse momentum ( $p_T$ ) and rapidity ( $y$ ).

aims to establish the system size dependence of the energy dependence of hadron production properties. This requires measurements for different pairs of colliding nuclei. The transition from the structure-less energy dependence for p+p interactions to the one with the structures related to the onset of deconfinement is expected to take place for collisions of medium size nuclei ( $A \approx 30 - 40$ ). Consequently, in order to localize this transition, data on collisions of light nuclei ( $A \approx 10$ ), medium nuclei ( $A \approx 30 - 40$ ) and heavy nuclei ( $A \geq 100$ ) will be taken in the coming years. The program started in 2009 with the energy scan of p+p interactions which are needed for a precise determination of the p+p baseline. The NA61 data taking status and plans are presented in Fig. 4. For comparison data collected by NA49 and STAR are also indicated.

First results from NA61 relevant to the study of properties of the onset of deconfinement are presented in Fig. 5 [11]. The rapidity and transverse mass spectra at mid-rapidity of negatively charged pions in all production p+C interactions at 31 GeV are compared to the corresponding NA49 results for central Pb+Pb collisions at 30A GeV [3]. The p+C rapidity spectrum is shifted towards target rapidity with respect to Pb+Pb collisions due to the projectile-target asymmetry of the initial state. The mean pion multiplicity in the forward hemisphere is approximately proportional to the mean number of wounded nucleons of the projectile nucleus. This reflects previous observations [4] that at the energy of the onset of deconfinement (30A GeV) the mean pion multiplicity in central Pb+Pb collisions agrees with that predicted by the Wounded Nucleon Model [12]. The shape of the transverse mass spectra at mid-rapidity changes from a convex form in p+C interactions to a concave one in central Pb+Pb collisions (with respect to the corresponding exponential fits). Within hydrodynamical approaches this is due to the significant collective flow in Pb+Pb collisions which is absent in p+C interactions.

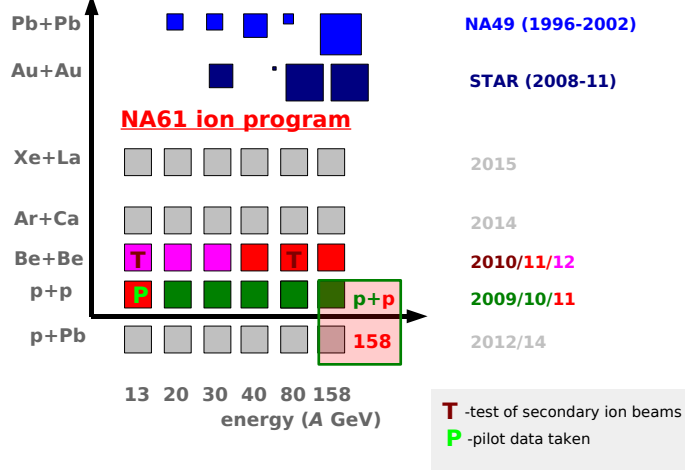


Figure 4: The NA61 data taking status and plans. For comparison data collected by NA49 and STAR are also indicated.

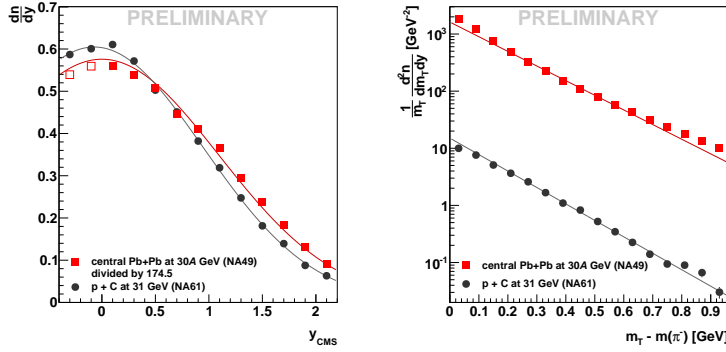


Figure 5: Rapidity (*left*) and transverse mass spectra at mid-rapidity ( $0 < y < 0.2$ ) (*right*) of negatively charged pions produced in all production p+C interactions at 31 GeV and central (7%) Pb+Pb collisions at 30A GeV. The Pb+Pb rapidity spectrum is divided by the mean number of wounded nucleons from the projectile nucleus.

### 3 Critical Point

The discovery of the onset of deconfinement discussed above implies the existence of QGP and of a transition region between confined and QGP phases. The most popular possibility concerning the structure of the transition region [13], sketched in Fig. 1, claims that a 1<sup>st</sup> order phase transition (thick gray line) separates both phases in the high baryonic chemical potential domain. In the low baryonic chemical potential domain a rapid crossover is expected. The end point of the 1<sup>st</sup> order phase



transition line is the critical point (the 2<sup>nd</sup> order phase transition).

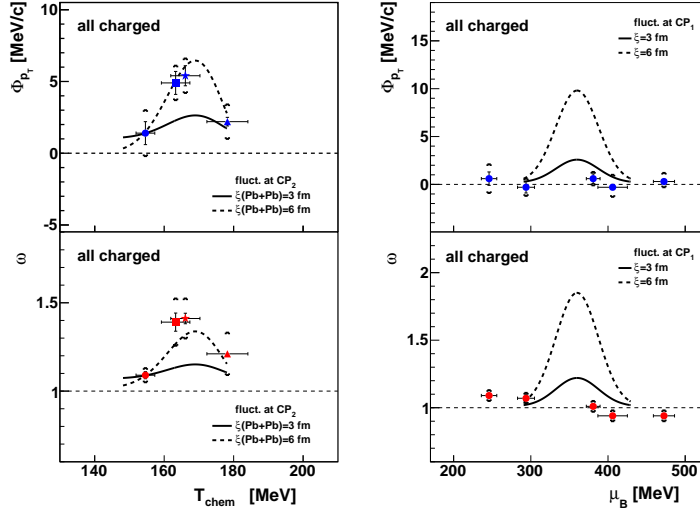


Figure 6: System size dependence of the  $\Phi$  measure of transverse momentum fluctuations (*top*) and scaled variance of multiplicity fluctuations (*bottom*) for charged hadrons in central collisions of two identical nuclei. *Left*: Results for p+p interactions and central C+C, Si+Si and Pb+Pb collisions at 158A GeV are plotted as a function of chemical freeze-out temperature [16]. *Right*: Results for central Pb+Pb collisions at 20A, 30A, 40A, 80A and 158A GeV are plotted as a function of baryonic chemical potential [16]. The lines present predictions for two hypothetical locations of the critical point CP1 ( $T = 147$  MeV,  $\mu_B = 360$  MeV) (right plot) and CP2 ( $T = 178$  MeV,  $\mu_B = 250$  MeV) (left plot).

The transition region can be studied experimentally in nucleus-nucleus collisions only at  $T$ ,  $\mu_B$  values which correspond to collision energies higher than the energy of the onset of deconfinement. This important conclusion is easy to understand when looking at Fig. 1. Signals of the critical point can be observed provided the freeze-out point is close to it (see Fig. 1 *right*). On the other hand, by definition the critical point is located on the transition line. Furthermore, the energy density at the early stage of the collision is, of course, higher than the energy density at freeze-out. Thus, the condition that the freeze-out point is near the critical point implies that the early stage of the system is above (or on) the transition line. This in turn means that the optimal energy range for the search for the critical point lies above the energy of the onset of deconfinement (see Fig. 1 *left*). This general condition limits the search for the critical point to the collision energy range  $E_{LAB} > 30A$  GeV.

The analysis of the existing experimental data [16] indicates that the location of the freeze-out point in the phase diagram depends on the collision energy and the mass of the colliding nuclei. This dependence is schematically indicated in Fig. 1 *right*. NA49 pilot data on collisions of medium and light mass nuclei suggest that signals of the critical point are visible in C+C and Si+Si collisions at

158A GeV [14, 15]. Example results on the dependence of fluctuations on system size at 158A GeV and on energy in central Pb+Pb collisions are shown in Fig. 6.

These results motivate a systematic search for the critical point. Similar to the study of the properties of the onset of deconfinement, a two-dimensional scan in collision energy and size of the colliding nuclei is required. As presented in Fig. 4 this scan was already started by NA61/SHINE and the complete set of data should be registered by the end of 2015. The basic components of the NA61 facility were inherited from NA49. Several important upgrades, in particular, the new and faster TPC read-out, the new Projectile Spectator Detector [17] and the installation of He beam pipes, allow to collect data of high statistical and systematic accuracy.

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